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Observation of ~ 500 keV Protons in Interplanetary Space with Mariner IV

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We report herein the observation of protons of kinetic energy $E_p \sim 500$ keV during a ten month period of interplanetary flight by the Mariner IV spacecraft.

The impulsive emission of energetic protons ($E_p \sim 1$ BeV) from the sun was shown first by Forbush.[1] Massive studies of the arrival at the earth of solar cosmic rays (protons, alpha particles, and heavier nuclei) in the energy range $\gtrsim 10$ MeV have been made by ionospheric methods,[2] by direct detection with satellite equipment,[3] and by other methods. The frequent occurrence of beams of protons of $E_p \sim 1$ MeV, below the energy and/or intensity threshold of previously used techniques, was inferred by Gregory[4] from 2.3 Mc/s ionospheric scatter measurements in Antarctica during 1959, 1960, and 1961. The inference of Gregory was confirmed and placed on a firm foundation by an extended series of direct interplanetary observations in late 1962 by Van Allen et al.[5] using a detector having an energy threshold $E_p = 0.5$ MeV on the Mariner II spacecraft.

The University of Iowa detector complement on the Mariner IV spacecraft consists of three thin window Geiger tubes (EON type 6213) and a thin (~ 35 micron) surface barrier nontotally depleted solid state detector (Nuclear Diodes, Inc.). A description of the detectors and of other experimental details has been published elsewhere.[6] In this note we are concerned primarily with results from the solid state detector which has two discrimination levels set to count protons in the energy ranges $0.50 \leq E_p \leq 11$ MeV (channel D_1) and $0.88 \leq E_p \leq 4$ MeV (channel D_2). Both channels are insensitive to galactic cosmic rays and to electrons of any energy, in the intensities found to be present by the Geiger tubes during the Mariner IV flight. The detector is equipped with a weak ${}_{95}Am^{241}$ source of alpha particles to provide assurance of its proper operation in flight. The conical collimator of the detector has a half angle of 30°, and the spacecraft is oriented continuously so as to point the center line of the collimator toward the inner solar system at 70° to the spacecraft-sun line. The absolute value of the unidirectional geometric factor is 0.065 ± 0.003 cm^2 sterad. Simultaneous data from the three Geiger tubes assure that all protons reported herein are in fact entering the solid state detector through its collimator and not through the protective shield.

Figure 1 shows the daily averages of the counting rates of channels D_1 and D_2 during ten months of interplanetary flight. Our apparatus performed properly throughout. "Cruise science" was commanded "off" for days 197-214 and days 243-245 of 1965 in order to use the spacecraft for other purposes and was finally commanded "off" on day 274 for an indefinite period, thus terminating the present series of observations.

The daily average of the counting rate of the Deep River neutron monitor (courtesy H. Carmichael) is also plotted in Figure 1 as is the daily sum of the three-hour geomagnetic disturbance indices K_p. These auxiliary data provide direct measures of the galactic cosmic ray intensity at the earth and of geomagnetic activity and thus, inferentially, a measure of the state of the interplanetary medium.

The observational duty cycle of each channel D_1 and D_2 is 11.161%. During a solid day of observations 9643 seconds of data are obtained from each channel. Hence, the statistical standard deviation σ of the daily average background rates of D_1 (0.069 count/sec) and D_2 (0.057 count/sec) is 0.0025 count/sec. A $3\ \sigma$ departure from the daily mean corresponds to a detection sensitivity for interplanetary protons having a unidirectional intensity j of 0.12 $(\mathrm{cm}^2 \text{ sec sterad})^{-1}$ in the energy ranges quoted above. Due to incomplete coverage in the preliminary data used in this report, typical values of σ are about 1.5 to 2 times as great as that for an ideal day.

In Table I there are listed 20 resolvable proton events having clear statistical significance. It is probable that a refined analysis of the final data will reveal other events of lesser intensity. Three electron events (not listed here) on days 25-28 May, 5-7 June, and 13-14 June 1965 have been reported[6] previously and attributed to direct solar emission.

The following summary remarks result from a preliminary study of the data:

(a) The counting rate of D_1 is significantly above that due to the calibration source for 10% of the period of observation 29 November 1964--20 April 1965, for 32% of the period of observation 21 April--30 September 1965, and for 24% of the entire period.

(b) There is a striking general anti-correlation between interplanetary proton activity and the intensity of galactic cosmic rays as measured by the Deep River neutron monitor (Figure 1).

It is tempting to regard this anti-correlation as physically significant and to suggest further that May 1965 is the "bottom" of a solar activity cycle.

(c) The most intense event of the series is that of 5-13 February 1965. It is the only one of the 20 events which is convincingly associated with a specific solar flare. In addition to the low energy protons shown in Figure 1, it contains a maximum omnidirectional intensity $J_o \sim 80\ (\mathrm{cm}^2\ \mathrm{sec})^{-1}$ of protons $E_p > 55$ MeV as measured with the shielded Geiger tube. The energy spectrum of the particles in this event is distinctly flatter than that of any of the other 10 events for which a significant spectral determination is feasible. The time profile of the intensity of the hard component in the 5-13 February event is reasonably well understood on the basis of free diffusion in the interplanetary medium. But the time profile of the intensity of the soft component as shown in Figure 1 is not so explicable.[7]

(d) The time-intensity profiles of most of the other 19 events reported here are roughly symmetrical and have widths in the range of one to several days.

(e) Also, in most of the other 19 events, the ratio of the counting rate of D_1 to that of D_2 is roughly constant throughout each event for which the D_2 rate is adequate for a significant determination. The differential energy spectra corresponding to these ratios can be represented by $dj/dE \approx \exp(-E/E_o)$ with E_o in the range 200 to 600 keV or by $dj/dE \approx E^{-\gamma}$ with γ in the range 2 to 4.

(f) Despite paragraph (b), in only 5 cases is there a convincing association between the occurrence of low energy protons at the spacecraft and a specific Forbush decrease at the earth; and in only 7 cases is there an associated geomagnetic sudden commencement (SC) at the earth (Table I). It appears that these associations weaken as the difference in heliocentric longitude of the spacecraft and the earth increases.

(g) The occurrence of successive events (with the exception of the first two) has no simple relationship to the period of rotation of the sun, as seen from the spacecraft, though it is possible that rotational periodicity is masked by the combination of several active centers at different heliographic longitudes and latitudes. A similar situation prevailed in our earlier observations[5] with Mariner II in late 1962.

The simple periodicity noted by Bryant et al.[8,9] for protons in the higher energy range $3 < E_p < 20$ MeV during a different time period may be attributable to differences in instrumental characteristics (i.e., considerably higher energy threshold and lower intensity threshold) or to the existence of a simpler activity pattern on the sun during their observations.

(h) During no one of the proton events (except the 5-13 February one) is there an intensity of associated electrons $E_e > 40$ keV exceeding a unidirectional value comparable to that of protons $E_p > 500$ keV (using data from the Geiger tubes, not shown herein).

There is little doubt that the observed low-energy protons owe their existence to the sun, either (A) by direct emission at essentially the energy observed or (B) by generation in turbulent regions of the solar wind in interplanetary space.[10]

Alternative (A) has been suggested[11] as an explanation of the low energy "storm protons" which were observed by satellites Injun I and Explorer XII on 30 September 1961. The gyro-radius ρ (in A.U.) of a non-relativistic proton of kinetic energy E (in MeV) in a magnetic field B (in gammas) is given by

$$B \rho = 0.97 \times 10^{-3} E^{1/2} .$$

Since interplanetary values of B are typically 5 gammas, the gyroradius of a 0.5 MeV proton is $\sim 1.4 \times 10^{-4}$ A.U. and it is reasonable to suppose that such protons can be confined to a conical bundle of somewhat twisted magnetic lines attached to the sun and co-rotating with it. In this frame of thought diffusion in a radial direction is supposed to be considerably more rapid than in the tangential direction. The interplanetary magnetic data of Ness and Wilcox[12] correspond, broadly, to such a supposition. Our observed time-intensity profiles may then be interpreted to imply the sweeping of such a populated bundle of magnetic lines across the spacecraft. The typical time duration of an event corresponds to a linear width of ~ 0.7 A.U. (5000 gyro radii) at a heliocentric radial distance of ~ 1.5 A.U. or to an angular width of the (bent) conical bundle of ~ 25 degrees. Further, it is supposed that the source of the protons is at the apex of the bundle in the solar corona.

Parker[10] rejects Alternative (A) on the grounds of "adiabatic deceleration in the expanding volume of the blast wave" and favors

Alternative (B), which presumably involves cooperative plasma phenomena, although he does not develop Alternative (B) to a convincing level. In a later, detailed paper[15] he shows that adiabatic deceleration is not necessarily of importance and we have also proposed a physically plausible model of interplanetary propagation which effectively circumvents the "adiabatic deceleration" objection to Alternative (A).

In the magnetospheric transition region and tail, which may be thought to be known examples of Alternative (B) on a pertinent physical scale, the intensities of electrons of $E_e > 40$ keV are at least several orders of magnitude greater than those of protons of $E_p > 500$ keV[13,14] (as is also the case in aurorae), contrary to observed fact (h) of the preceding summary.

We conclude that both Alternatives (A) and (B) and perhaps some combination of them survive this qualitative discussion but we continue[11] to favor (A) as a working hypothesis.

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Table I

Proton Events Observed with Mariner IV

28 November 1964--1 October 1965

Dates 1965 (Incl.)	Days 1965 (Incl.)	Heliocentric Radial Distance of Spacecraft (A.U.)	Difference in Heliocentric Ecliptic Longitudes of Spacecraft and Earth (Degrees)	Maximum Unidirectional Intensity, j $0.50 \leq E_p \leq 11$ MeV $(cm^2 \text{ sec sterad})^{-1}$	Possibly Pertinent Solar Activity as Seen from the Earth
8-12 January	8-12	1.06	+ 1.7	4.3 ± 0.3	Imp. 2 Flare 6 Jan. 0810 UT
5-13 February	36-44 *F	1.15	- 1.9	140	Imp. 2^+ Flare 5 Feb. 1750 UT
20 April	110 *F	1.39	-24.5	0.4 ± 0.1	Imp. 2 Flare 15 Apr. 0915 UT
7-8 May	127-128	1.44	-32.0	0.8 ± 0.2	-----
26 May	146	1.48	-40.3	0.9 ± 0.3	-----
27 May	147	1.48	-40.8	1.1 ± 0.3	-----
1-5 June	152-156 *	1.50	-44.2	3.0 ± 0.2	Imp. 2 Flare 28 May 0916 UT
12-19 June	163-170 *F	1.52	-50.4	1.7 ± 0.5	Imp. 3 Flare 9 June 0559 UT
21 June	172	1.53	-53.2	0.6 ± 0.2	-----
28 June -- 1 July	179-182	1.54	-57.0	4.2 ± 0.2	Imp. 2^+ Flare 28 June 1020 UT
2-3 July	183-184	1.54	-58.4	1.1 ± 0.2	-----
4-6 July	185-187 ●	1.55	-59.7	2.1 ± 0.2	-----
10 July	191 ●	1.55	- 62.2	0.4 ± 0.1	-----
13-15 July	194-196 F	1.55	- 64.3	6.4 ± 0.3	-----
No Observations 16 July--2 Aug.	197-214	----	----	-----	-----
3-4 August	215-216	1.57	- 74.4	1.4 ± 0.2	-----
6-9 August	218-221	1.57	- 76.4	6.6 ± 0.3	-----
17 August	229 *F	1.57	- 81.0	0.4 ± 0.1	Imp. 2 Flare 15 Aug. 0615 UT
26-30 August	238-242	1.57	- 86.9	6.0 ± 0.3	-----
No Observations 31 August --2 Sept.	243-245	----	----	-----	-----
22-24 Sept.	265-267	1.56	-100.0	0.8 ± 0.2	-----
25-26 Sept.	268-269	1.56	-101.6	0.5 ± 0.1	-----

Notes: (a) Heliocentric ecliptic longitude is measured counterclockwise as viewed from the north ecliptic pole.

(b) Maximum intensity is derived from the highest four-hour average counting rate during the event.

(c) The right hand column is extracted from the monthly "Compilations of Solar-Geophysical Data" of the U. S. Department of Commerce NBS/CRPL, Boulder, Colorado.

(d) Positional coordinates are from Jet Propulsion Laboratory ephemeris IBSYS-JPTRAJ-SFPRO 111464 of 15 December 1964.

(e) In the second column ● denotes a magnetic SC and F denotes a clear Forbush decrease in galactic cosmic ray intensity observed approximately simultaneously at the earth.

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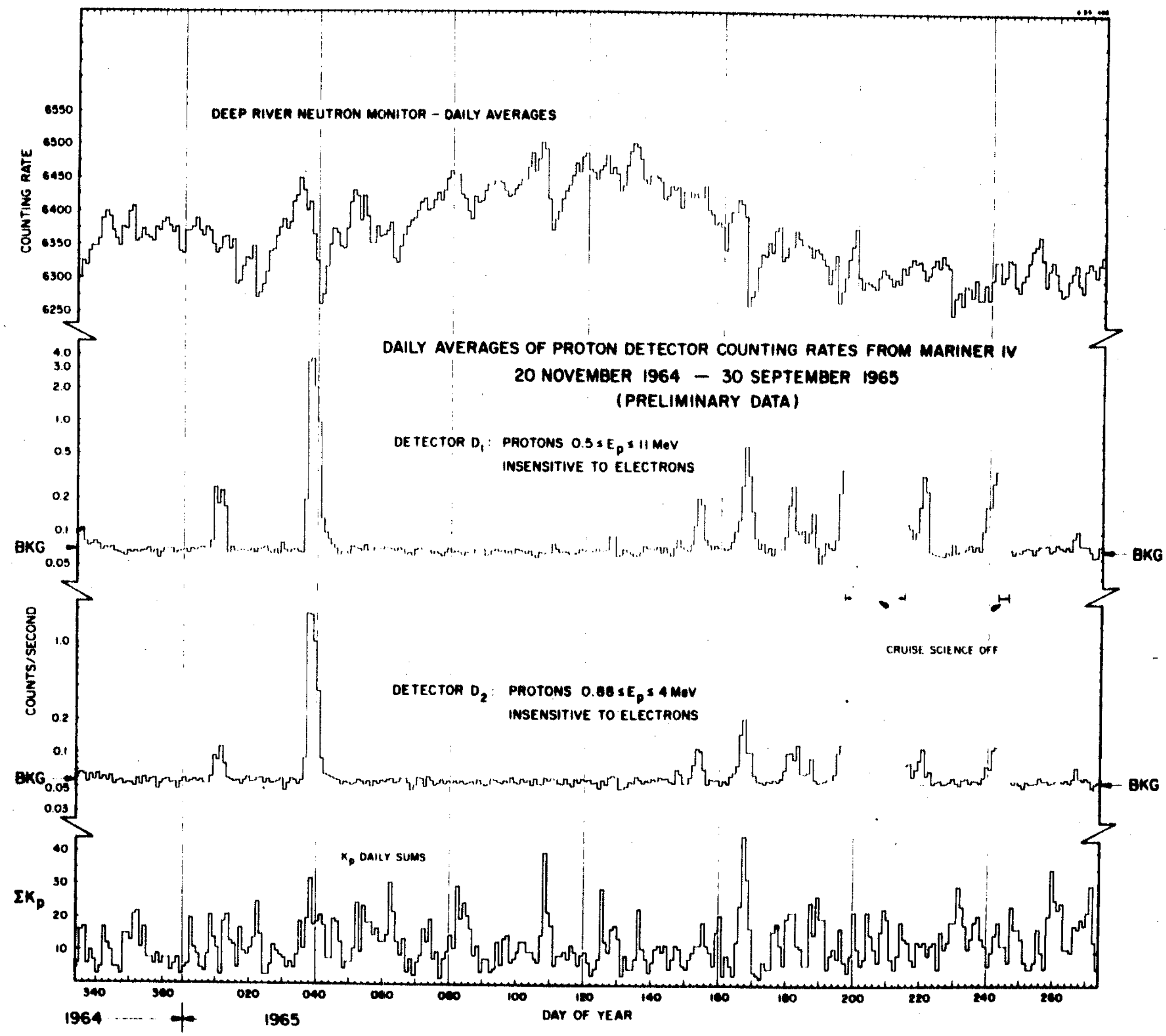

Figure 1